

# OPTIMAL SPECTRUM PLANNING AND MANAGEMENT WITH COALITION JOINT SPECTRUM MANAGEMENT PLANNING TOOL (CJSMPT)

Randy Poe, Raymond Shaw, Harris Zebrowitz,  
William Kline, and William Heisey  
Lockheed Martin Advanced Technology Laboratories  
Cherry Hill, NJ

Frank Loso and Yoram Levy  
U.S. Army Communications Electronics Research  
Development and Engineering Center  
Fort Monmouth, NJ

## ABSTRACT

*The Coalition Joint Spectrum Management Planning Tool (CJSMPT) has been designated as Spiral I of the Global Electromagnetic Spectrum Information System (GEMSIS) program, which is intended to provide next-generation capabilities for integrated spectrum operations across the entire Department of Defense, in addition to interoperability with federal, state, and local government spectrum agencies and coalition forces. This paper describes the use of CJSMPT in automating key spectrum management planning processes including Joint Task Force (JTF) requirements generation and spectrum interference mitigation. This paper will also review additional CJSMPT capabilities, its architecture, and the current development effort.*

## OBJECTIVES AND APPROACH

Lessons learned from recent operations, exercises, and training events confirm that current operational and tactical radio frequency (RF) spectrum planning and management practices do not keep pace with operations tempo. Examples include inability to mitigate the effects that Counter Radio-Controlled Improvised Explosive Device Electronic Warfare (CREW) have on other Blue Force RF-spectrum-dependent systems, sub-optimal use of RF spectrum by critical unmanned aerial systems due to inefficient frequency re-assignment capability, and degraded land-based communications associated with on-the-move forces. The centralized spectrum management database, SPECTRUM XXI, is not designed to handle these systems. Many of the operational spectrum managers are forced to make worst-case requests for frequencies because of the lack of suitable analysis tools. As a result, warfighters deployed in operations today face severe limitations in accessing the RF spectrum. The problem is compounded by a lack of automation and information exchange among tools used to manage frequency assignments and RF spectrum usage. CJSMPT is currently developing capabilities to resolve these issues through the automation of spectrum management and efficient

simulation-based analysis, advanced visualization, and spectrum optimization tools.

CJSMPT is a Joint Capability Technology Demonstration (JCTD) managed by the U.S. Army Communications-Electronics Research Development and Engineering Center (CERDEC) with guidance from the Joint Staff and Combatant Commands (COCOMS). The JCTD began in May 2006. Lockheed Martin Advanced Technology Laboratories (LM ATL) is the prime contractor, working in cooperation with Alion Science; SYColeman; Battle Command Battle Lab (BCBL), Fort Gordon; Joint Spectrum Center (JSC); and Penn State University. During the first 11 months (Phase I) of the program, CJSMPT developed tactical spectrum management and planning capability to mitigate the effects of electronic warfare (EW) operations on Blue Force military communications systems during maneuver operations. Phase I produced Version 1.0 of CJSMPT, which was delivered to CERDEC in June 2007. This software underwent a field assessment by the Central Command (CENTCOM) in Iraq during September and October 2007. This assessment resulted in a number of suggested enhancements that are now being implemented in Phase II. Phase II enhancements will also provide additional capabilities that include a spectrum planning and collaboration capability for the COCOM Joint Frequency Management Office (JFMO) and their components. In the presence of a Joint Task Force (JTF), CJSMPT can provide this same planning and collaboration capability to the Joint Spectrum Management Element (JSME) spectrum managers as well as all subordinate and peer spectrum managers. This capability allows the spectrum managers at all levels of command to collaboratively plan and accelerate the spectrum management processes during all phases of JTF planning, execution, and post-deployment phases. These new capabilities provide automation to the JTF spectrum management lifecycle (CJCSM 3320.01B). This lifecycle was developed for joint spectrum managers as a guide to follow in establishing functional and efficient JTF spectrum management processes. CJSMPT provides Spectrum Requirements Advisor (SRA) and Spectrum Plan Advisor (SPA) automation tools to assist the spectrum manager throughout these processes.

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The SRA supports spectrum managers' planning for: a new theatre, a major reorganization, or post-deployment training. The SRA automatically generates a reuse plan that includes the minimum quantity and characteristics of electromagnetic spectrum required to support operations. This capability will result in less spectrum use and allow better allocation of the RF spectrum. The SRA enables the user to generate "pool-type" requirement requests or produce specific frequency requests. These requests are output in Standard Frequency Action Format (SFAF), which is processed by SPECTRUM XXI. SPECTRUM XXI is a client/server, Windows-based software system that provides frequency managers with a single information system that addresses spectrum management automation requirements. Resources obtained from SPECTRUM XXI are loaded into CJSMPPT and are applied to unassigned radio nets, allowing the reuse of spectrum to populate all radio nets in the Joint Communications Electronics Operating Instruction (JCEOI). Presently these tasks are largely manual and accomplished with a variety of incompatible planning tools which results in over-estimation and use of spectrum resources.

To most in the spectrum management community, interference mitigation is limited to conflict detection; it does not include recommending frequency changes to resolve conflicts. The CJSMPPT Spectrum Plan Advisor (SPA) interference mitigation capability does both. The SPA can recommend ways to resolve unacceptable electromagnetic interference from non-electronic warfare (EW) devices as well as EW devices, minimizing "Blue on Blue" and "CREW on Blue" spectrum encroachment. This

capability facilitates coordination between the electronic warfare officer (EWO) and spectrum manager. This relationship is critical to ensure the successful accountability and employment of EWO designated EW missions and for improved RF-spectrum situational awareness.

LM ATL is also developing the Army's Communications Planner for Operational and Simulation Effects with Realism (COMPOSER), a CERDEC Army Technology Objective (ATO) developing capabilities for the warfighter to enable effects-based communication planning of equipment configuration for mobile forces. As part of this capability, COMPOSER is developing a Communications Effects Simulator (CES) that predicts potential interference while accounting for terrain, equipment characteristics, and force movement. This technology is being leveraged directly into CJSMPPT. The SRA and SPA algorithms rely heavily on the CES results of predicted potential interference to perform their operation.

## ARCHITECTURE OVERVIEW

CSMPT runs on a standard ACES/JACS laptop. These laptops are already in use by all branches of the armed forces. The CJSMPPT architecture (Figure 1) is comprised of eight key components that coordinate to perform the spectrum management planning, requirements analysis, and RF conflict mitigation processes:

- *User Interface* (Figure 2) coordinates overall operation of the system including editing and viewing of scenario

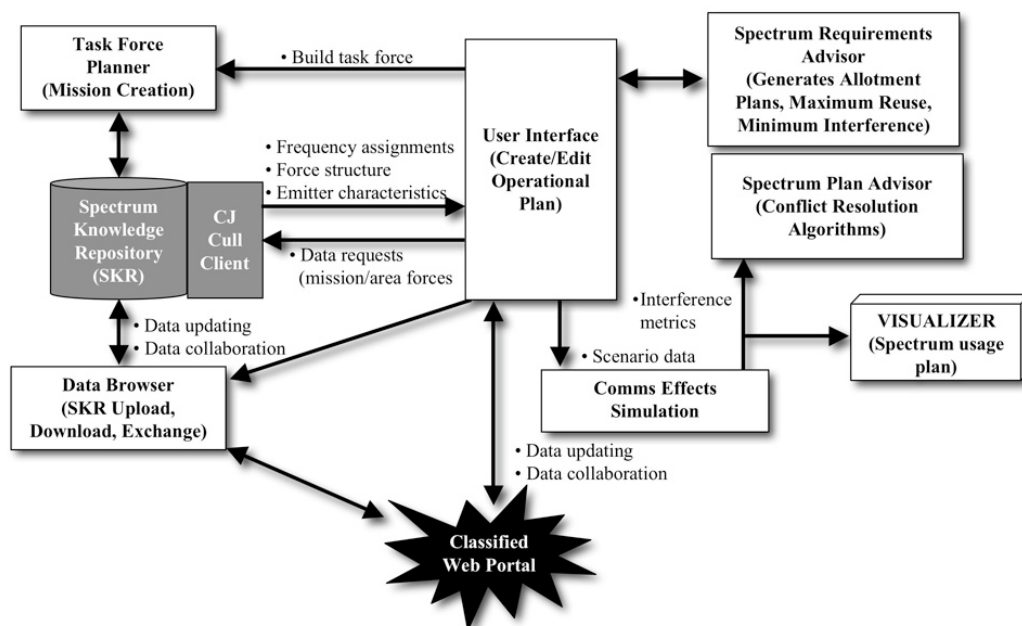


Figure 1. CJSMPPT Architecture

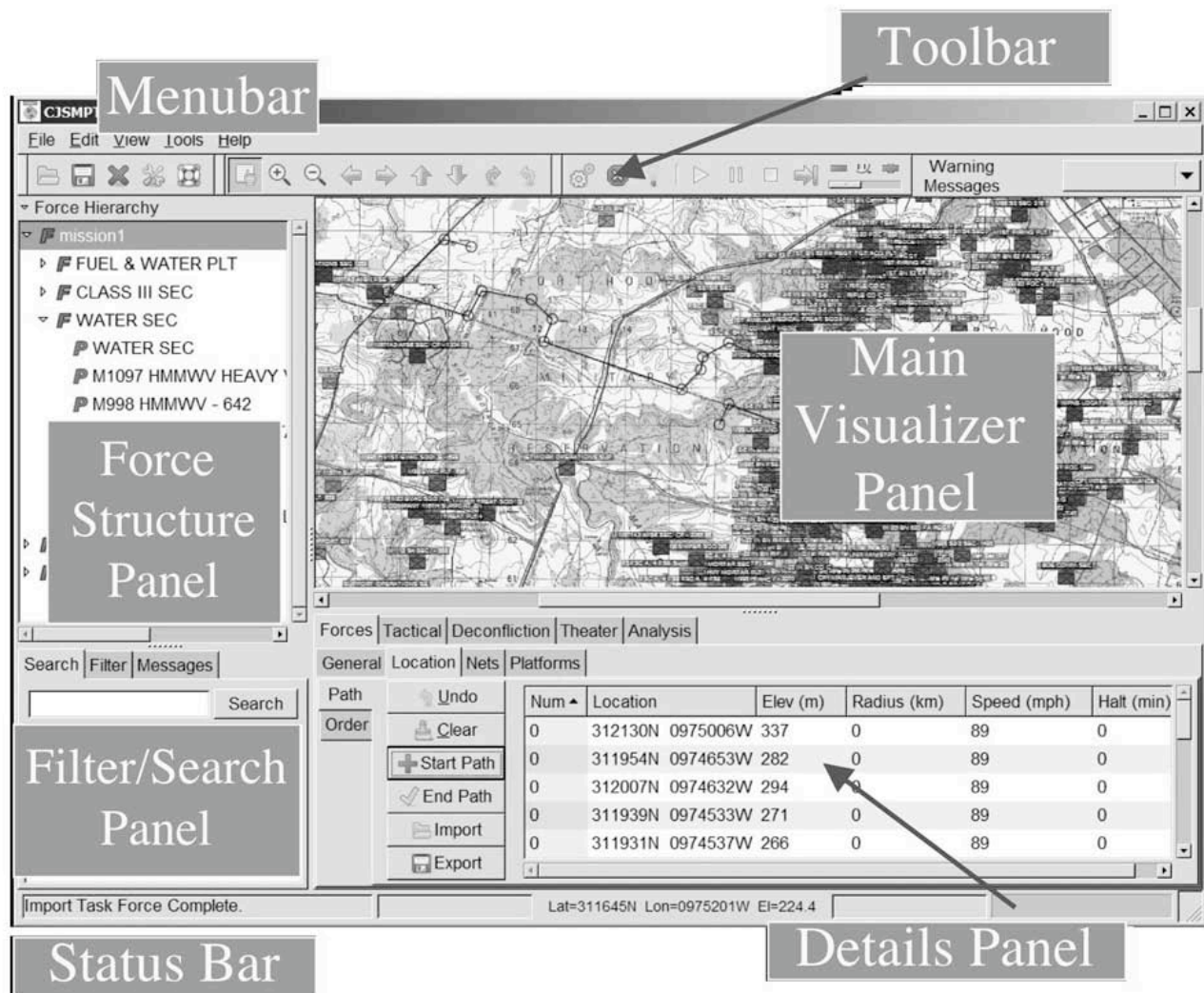


Figure 2. CJSMP User Interface

operational equipment parameters, force location, and movement information. It also provides capabilities to generate formatted reports such as Joint Spectrum Interference Resolution (JSIR) formatted output.

- *Communication Effects Simulator (CES)* simulates the planned missions to predict if conflicts will arise. CES is based on the LM ATL CSIM Simulator [1]. The CJSMP CES models movement, equipment characteristics including power and waveform, and antenna characteristics (i.e., height, polarization, directionality, terrain effects) and predicts if interference may exist between equipment based on the planned scenario.
- *Spectrum Plan Advisor (SPA)* suggests frequency modifications required to mitigate interference predicted by CES. The SPA can also suggest an initial assignment plan when presented with a frequency allotment

(frequency pool). The user can specify net priority based on mission QoS requirements that the SPA uses to prioritize resolving interference without effecting mission critical nets.

- *Spectrum Requirements Advisor (SRA)* is used prior to frequency assignment. Given a force structure location and movement, nets and equipment descriptions, it automatically generates a reuse plan as well as providing the spectrum manager the minimum spectrum requirements needed for an interference-free operation. The outputs are based on CES prediction of interference between equipment. It can also suggest specific frequencies for nomination and assignment taking into account user defined and/or Host Nation Allocation Tables.
- *Visualizer* shows force location and movement on a 2D/3D map display and shows spectrum use including

EW effects. The Visualizer also enables users to view—in color-coded format—the RF radiation and allows the spectrum manager to interactively specify location and movement of forces on a map. *Spectrum Knowledge Repository (SKR)* contains key scenario data to support simulation of the mission (force structure, emitter characteristics, Joint Communications-Electronics Operations Instructions [JCEOI] data, etc.). The SKR is populated from existing databases and sources including JSC Equipment Tactical and Space (JETS), SPECTRUM XXI and JACs. Also, inter-record linkages are formed (e.g., JCEOI with equipment characteristics) to provide a more detailed explanation of the JCEOI. Data are extracted from the local SKR by the Cull Client that formats the data in XML read by the user interface.

SKR need to be approved within the chain of command. This Data Browser component supports uploads from the local SKR to the master SKR, downloads from the master SKR to the local SKR, and a two-way exchange with another CJSMPPT user. A classified web portal provides the service-oriented architecture with mechanisms for data exchange.

## AUTOMATED PLANNING OPERATION

The requirements analysis problem is to determine the minimum pool (number of channels and their bandwidth) required to satisfy all spectrum needs while ensuring conflict free operation. The planner begins this task by defining a scenario using the Joint Task Force Planning Tool (J-TFP). The planner can view and edit specific forces or build forces from the generic force templates. Specific forces are background forces already in the area of interest (AOI) and contain nets with assigned frequencies. Generic forces are customized by the user from generic force templates and contain nets that do not have assigned frequencies. Any mix of specific and generic forces may be used in defining the scenario. When formulating JTF requirements, component-level spectrum managers will define the scenarios for their areas of responsibility. Other aspects of the scenario, such as location and force movement, can also be entered. These forces are then electronically uploaded to the Joint Spectrum Management Office/Joint Spectrum Management Element (JFMO/JSME) planner through SKR data exchange. The JFMO/JSME loads the scenario into the CES to simulate the planned mission. Using the CES results, the SRA is invoked to suggest the minimum spectrum requirements

- *Joint Task Force Planner (J-TFP)* enables users to develop scenarios to be analyzed by the CES. Background information such as force structure, emitter characteristics, and JCEOI data, are constructed from any of the following: area forces (based on collaborated SKR data within the selected theatre), pre-built generic forces templates, as well as forces structure data extracted from the services existing databases (e.g., the Marine Corps Total Force Structure Management System).
- *Data Browser* provides the ability to collaboratively plan (Figure 3) for communication needs within a joint and/or coalition environment. Each CJSMPPT user has an SKR local to their workstation that is used during the planning phases. The SKR administrator manages a master SKR that allows for a plan to be shared among all other spectrum managers. Permanent changes in the master

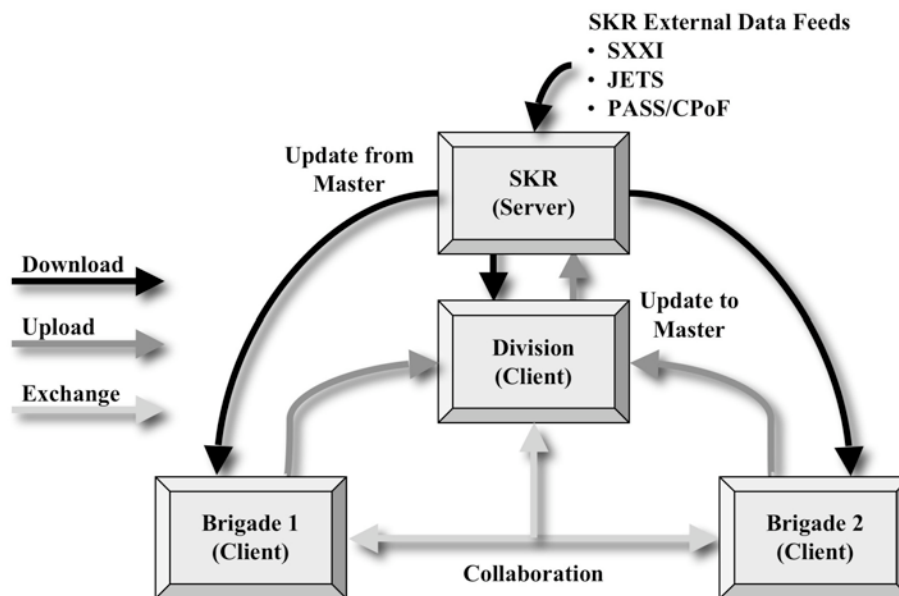


Figure 3. Two-way Spectrum Knowledge Repository (SKR) Transaction-based Data Interchange

for the unassigned nets and generate a reuse plan detailing which nets can share frequencies. A Spectrum Requirements Summary Report is generated and displayed as tabs within the user interface. It can also be exported into an Excel® spreadsheet. Requirements are then exported from CJSMPPT as SFAFs to SPECTRUM XXI. Within SPECTRUM XXI frequency resources are generated and become “frequency assignments.” The frequency resources obtained from SPECTRUM XXI are returned to CJSMPPT and automatically applied to nets requiring frequencies. An additional SFAF file is then generated to update the SPECTRUM XXI records with more accurate frequency use information (i.e., the actual intended location, power, JCEOI net assignment, etc.).

The conflict mitigation problem is to determine the minimum number of frequency changes needed to mitigate or minimize conflicts given a fixed pool of resources. Automated spectrum conflict mitigation also begins when the planner defines a scenario using the Joint Task Force Planning Tool (J-TFP). Data populated from the local SKR can be viewed and edited through the J-TFP. Location and movement of forces is also specified. The scenario features are then fed into the CES to simulate the scenario. The CES then predicts if interference may occur between assigned equipment in the designated AOI. Interference reports, displayed as tabs, are based on the CES prediction. The reports can be saved in various formats such as Excel® and CSV. Based on the CES results, the SPA is invoked to suggest frequency modifications to reduce or eliminate the interference predicted. Only frequencies within the AOI are considered as candidates to mitigate the interference. The SPA generates a suggested spectrum plan that makes minimal changes to the original plan while simultaneously minimizing or removing all RF interference. The Visualizer can be invoked to provide a 2D or 3D visualization of the spectrum use predicted by the CES including predicted interference and spectrum coverage. The SRA and SPA use a common algorithm framework as described in the following.

## AUTOMATED SPECTRUM PLANNING FRAMEWORK

Spectrum requirements and conflict mitigation optimization is a multi-dimensional problem that involves space, time frequency, modulation-code and other dimensions. To perform this optimization, CJSMPPT uses a graph-theoretic representation of interference in which *nodes* of the graph represent nets, and *edges* (connections between nodes) represent the potential for interference. A key aspect of the interference graph is that the interference is integrated over time based on simulation of the scenario. This allows CJSMPPT to do on-the-move planning. A

connection between nodes means that at some time during the scenario the corresponding nodes interfere if assigning conflicting resources.

We have adapted the idea of *graph coloring* to these planning problems. In graph theory, the graph-coloring problem is the problem of determining the minimum set of colors such that no two nodes connected by an edge have the same color. Any coloring in which this condition is satisfied is considered *valid*; thus, the graph coloring problem is the problem of finding the smallest set of colors needed to form a valid coloring. Our approach uses a standard graph-coloring model, where different colors (different frequencies) sufficed to avoid interference [2]. In practice, transmitters and receivers have finite bandwidth and harmonics (and other real-world considerations), and so a transmitter can cause interference to a receiver that is tuned to a different frequency. CJSMPPT has developed and implemented a flexible Spectrum Planning Automation Framework (Figure 4) that has proven to be sufficiently versatile to represent all the operational considerations needed to provide requirements analysis and interference mitigation optimization. Application-specific rules and constraints are handled by logic within the Graph Construction, Node Ordering, Pool Generation and Candidate Selection modules. The details are described in the following sections.

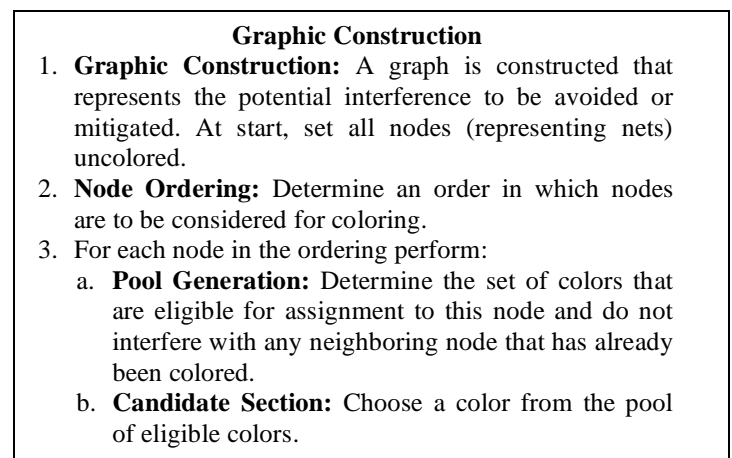


Figure 4. Spectrum Planning Automation Framework

Construction of a representative graph is key to the success of automated spectrum planning. The graph is built from data calculated by the CES, which incorporates terrain propagation models, platform motion, antenna gain, and modulation effects. Despite this high level of fidelity, the CES is able to simulate thousands of platforms and millions of potential source-victim interference pairs on time scales of a few minutes, short enough to allow for multiple simulation runs during the planning process.



The graph is constructed based on a worst-case severity matrix calculated by the CES. The severity is calculated between each pair of nodes as follows:

$$S_{sv} = \max(P_s - L_p + G - T_v)$$

where:

- $S_{sv}$  = severity matrix element for source  $s$  and victim  $v$
- $P_s$  = source power
- $L_p$  = propagation loss
- $G$  = antenna gains
- $T_v$  = victim sensitivity (interference threshold)

and the maximum is taken over the entire scenario duration. Maximum severity values exceeding 0 dB (received in-band power exceeds the threshold at any time) indicates potential for interference.

Though the graph coloring problem of finding an optimal coloring is known to be NP-hard (the runtime grows exponentially with the problem size), the “greedy” (largest or worst items first) heuristic approach gives good solutions in polynomial time. In the standard greedy algorithm, the nodes are ordered in descending order of the number of connections to other nodes. This number is called the *degree* of the node, and the greedy heuristic begins with the nodes of highest degree. In Node Ordering, we generalize the decreasing-degree heuristic with a sort on four properties in order:

- *Node Priority*: If there is a need for trade-offs, the commander may be willing to sacrifice the performance of some nets in favor of more critical ones.
- *Bandwidth*: Larger-bandwidth nets require more resources, and in an extension of the greedy concept such nodes are considered for assignment first; this is a common approach in resource allocation problems such as bin packing.
- *Frequency Locking*: Some nets have frequencies (i.e., frequencies on the Joint Restricted Frequency List [JRFL]) that are not subject to change.

CJSMPT allows users to specify priorities and locking manually. In addition, other instances are handled by automated setting of the priority and lock state. For example, the SPA supports EW deconfliction where the frequency changes are restricted to the minimum set needed to avoid conflicts with EW operations. For EW deconfliction, EW devices and the nets that they impact are given highest priority; all others are locked. In requirements analysis, there are background emitters that

are part of the electromagnetic battlespace (EMB) but not under JSME/JFMO control. These nodes are included in the interference graph but are automatically locked and are not counted in the requirements.

Pool Generation provides a list of candidate colors (frequency assignments) that are considered legal assignments to the given node. This selection is based on which colors have already been assigned to neighboring nodes, which colors are suitable for the given equipment, and other policies and constraints that may restrict the available choices. For requirements analysis, the Pool Generation module in the SRA begins by dividing the tunable range up into steps appropriate for the given net (e.g., the range of 30 to 88 MHz may be divided by the tuning increment). These frequencies represent frequency requirements, which are ultimately sent by CJSMPT to SPECTRUM XXI in exchange for actual frequencies. For conflict mitigation, the Pool Generation module formulates frequency pools based on frequencies already being used in the theater. The SPA, sorts these frequencies into groups based on a common bandwidth, emission designator, and equipment tuning range. In many cases, there are restrictions on the frequencies available to military operations, such as bands, which the assignment authority (e.g., host nation or FCC) reserves. In both SRA and SPA these frequencies are eliminated from the pool. The remaining frequencies are checked against any neighbors that have been previously colored to see whether the assignment can be made without causing new interference. As mentioned previously, this assessment depends not only on the two frequencies but also on the specific characteristics of the equipment being used.

The Candidate Selection process implements operational rules for how frequencies are assigned. The rules include:

- Re-use colors previously assigned.
- Guard band rules that restrict assignment of frequencies too close together (i.e., based on physical proximity of the nets).
- Assignment rules (e.g., “use lower frequencies before higher frequencies,” “maximize spacing,” or “maximize reuse”).

By use of either deterministic rule sets or random choice from suitably weighted probability distributions, the Candidate Selection function can capture a wide variety of knowledge on how frequencies are selected by operational spectrum managers.

## CONCLUSION

CJSMPT is developing capability that will give warfighters the ability to rapidly predict conflicts and optimize spectrum use for mission success. Currently, the lack of a robust and collaborative spectrum-planning tool can result in the under-assignment of spectrum for a given area. Many of the operational spectrum managers are forced in to a “worst case” scenario every time they request frequencies. This causes SPECTRUM XXI to believe there is no spectrum available for a given AOI. This lack of ability to effectively manage our spectrum dependency in the joint warfighting environment is a critical shortfall, which CJSMPT will rectify. Our spectrum management deficiencies have significantly constrained our component and coalition forces ability to operate.

During the early planning phase of an operation, CJSMPT will provide spectrum managers capability to enable distributed formulation of spectrum requirements, request frequencies and make preliminary assignments. In addition, CJSMPT will provide an enhanced capability to identify potential RF spectrum conflicts before they occur and enable development of solutions to the conflicts and provide the means to inform leadership of RF spectrum related impacts to operations. Furthermore, CJSMPT will assist warfighters in resolving RF spectrum conflicts identified during the execution phase of a mission so that dynamic changes can be made to critical command and control links. Finally, during the “post deployment phase” CJSMPT will analyze information from “lessons learned” documents submitted by all the forces participating in operations abroad so that they may be considered during the planning and execution of future missions.

This paper describes the underlying CJSMPT architecture developed to accomplish these tasks. We presented the CJSMPT planning algorithm framework and described how it is being applied to JTF spectrum requirements analysis and spectrum conflict mitigation. The SRA and SPA tools will help the tactical spectrum manager to minimize interference and maximize spectrum reuse in an automated fashion. In addition the underlying technology can help strategic planners. As an example, CJSMPT’s simulation and automated JTF requirements analysis capability can be applied to assessing the spectrum needs for new equipment. This analysis could affect acquisition decisions and identify interoperability issues with legacy equipment prior to deployment saving money and potentially saving lives. A Joint Military Utility Assessment (evaluation of the military utility of joint systems) for CJSMPT is scheduled for early 2009. Upon successful completion of this evaluation CJSMPT will be deployed to support joint spectrum operations.

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